Clouds and the Earth's Radiant Energy System (CERES)

Validation Document

Validation of CERES Surface Radiation Budget (SRB) (Subsystem 4.6)

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(Subsection 4.6)

4.6.1INTRODUCTION
4.6.1.1Measurement & Science Objectives

The CERES subsystem 4.6 endeavor is concerned with the retrieval of both the shortwave and longwave components of the surface radiation budget (SRB) fluxes. This is achieved through the use of established parameterized radiative transfer algorithms which derive the surface fluxes directly from top-of-atmosphere (TOA) radiances measured by the CERES instrument aboard satellites such as the Tropical Rainfall Measuring Mission (TRMM), EOS-AM-1, and EOS-PM-1. These direct TOA-to-surface transfer relationships contrast with the CERES subsystem 5.0 (Surface and Atmospheric Radiation Budget or SARB) procedures which are based upon complex physical models requiring detailed knowledge of atmospheric conditions. It should be noted, however, that the parameterized transfer algorithms for CERES subsystem 4.6 have been formulated from comprehensive studies involving detailed radiative transfer procedures (*e.g.*, line-by-line calculations). The ultimate goal behind the SRB procedure is to provide reliable yet efficient algorithms applicable to conditions encountered over a substantial portion of the Earth.

To accomplish the goals of CERES subsystem 4.6, separate radiative transfer algorithms have been developed for the shortwave (< 5.0 m) and longwave (> 5.0 m) regions of the spectrum.

For shortwave radiation, evidence has been presented (see *e.g.*, Cess *et al.*, 1991; Li *et al.*, 1993a) that a straightforward relationship exists between TOA and surface fluxes. This premise forms the basis of the Li *et al.* (1993a) shortwave algorithm which is detailed in Algorithm Theoretical Basis Document (ATBD) subsection 2.2.4 (now 4.6.1). Recent studies (see *e.g.*, Cess *et al.*, 1995; Ramanathan *et al.*, 1995), however, indicate that important physical processes may have been overlooked with the consequence that significant contributions to the radiation field may have been neglected. Specifically, Cess *et al.* (1995) and Ramanathan *et al.* (1995) present evidence that for cloudy-sky conditions shortwave absorption occurs in excess of that predicted theoretically. The conclusions of Cess *et al.* (1995) and Ramanathan *et al.* (1995) are further supported by the field work of Pilewski and Valero (1995) which deals with aircraft measurements of shortwave fluxes made within the cloudy tropical atmosphere. Nevertheless, recent studies by Li *et al.* (1995a) and Chou *et al.* (1995) have been unable to obtain similar shortwave flux enhancements and thus do not support the conclusions of Cess *et al.* (1995) and Ramanathan *et al.* (1995). A resolution of this issue is dependent upon the acquisition of data from field campaigns such as the ARM Enhanced Shortwave Experiment (ARESE), and from operational surface networks such as the NOAA Surface Radiation (SURFRAD) network in the U.S. and the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN). Until a comprehensive determination is made, however, a reasonable course of action is to retain the existing Li *et al.* (1993a) shortwave algorithm, at least for the early stages of the validation study.

For longwave radiation, no algorithm has been successful in retrieving the net surface flux directly from the TOA flux. While the difficulties are substantial for clear-sky conditions, they are particularly

vexing for cloudy-sky conditions where strong longwave absorption in clouds results in a complete decoupling of the TOA and surface longwave radiation fields (Stephens and Webster, 1984). Nevertheless, as noted by Gupta *et al.* (1994), by taking into consideration certain meteorological data in conjunction with retrieved TOA fluxes, a successful alternative approach can be formulated to obtain the surface fluxes. Indeed, two successful procedures have been developed, one for the clear-sky case, and one for the total-sky case. The Inamdar and Ramanathan (1994) algorithm, detailed in ATBD subsection 4.6.2, calculates the surface fluxes for clear-sky conditions using TOA radiances from both the longwave broadband and window (8.0 -12.0 m) channels. This clear-sky longwave algorithm is therefore in the position to take full advantage of both the CERES longwave broadband and window channels. For total-sky and cloudy-sky conditions, Gupta (1989) has developed an algorithm, detailed in ATBD subsection 4.6.3, which has proven useful in retrieving surface fluxes from TOA fluxes for cloudy conditions (see also Gupta *et al.*, 1992).

4.6.1.2Missions

The CERES instrument is scheduled to fly aboard the TRMM satellite and on the EOS-AM-1 and EOS-PM-1 platforms. Should follow-on missions be approved, it is anticipated that the CERES instrument will also fly aboard those satellites.

4.6.1.3Science Data Parameters

The selected algorithms will provide data parameters as part of the Single Satellite Flux (SSF) data product by calculating each of the surface radiation budget flux components, namely: shortwave, clear-sky longwave, and cloudy-sky longwave. The input data for these algorithms are provided by three sources: CERES TOA fluxes for each footprint, MOA (Meteorological, Ozone, and Aerosol) data, and CERES cloud properties for each footprint. Overviews of the three models are located in the CERES ATBD. Specifically, the Li *et al.* (1993a) shortwave algorithm is discussed in subsection 2.2.4 (now 4.6.1), the Inamdar and Ramanathan (1994) clear-sky longwave algorithm is discussed in subsection 4.6.2, and the Gupta (1989) cloudy-sky longwave algorithm is discussed in subsection 4.6.3. The input parameters required and output parameters provided by the algorithms are as follows.

a) Shortwave: The input parameters required by the Li *et al.* (1993a) shortwave algorithm include reflected TOA shortwave flux (W/m2), solar zenith angle, and from MOA: precipitable water (g/cm2). It is important to note that no information is required concerning either the surface conditions or the presence/absence of clouds. The output of this routine is the net shortwave flux at the surface (W/m2).

b) Longwave Clear-Sky: The input parameters required by the Inamdar and Ramanathan (1994) longwave clear-sky algorithm include clear-sky TOA longwave broadband (> 5.0 m) flux (W/m2), clear-sky TOA longwave window (8.0 - 12.0 m) flux (W/m2), and from MOA: surface temperature (K), atmospheric temperature profile (K), and total column precipitable water vapor (g/cm2), and aerosol *visible* optical depth. Another potentially important input, the surface emissivity, may also be taken into consideration in the future. The output includes: downward longwave broadband surface flux (W/m2), downward longwave window surface flux (W/m2), and downward non-window surface flux (W/m2).

c) Longwave Cloudy-Sky: The input parameters required by the Gupta (1989) longwave cloudy-sky algorithm are fractional cloud amount, cloud base pressure (hPa), cloud top pressure (hPa), and cloud top temperature (K) from the CERES Footprint and Cloud Properties, and from MOA: surface temperature (K), atmospheric temperature profile (K), and atmospheric water vapor amount (g/cm2). The output includes downward longwave surface flux (W/m2) and net longwave surface flux (W/m2).

4.6.2VALIDATION CRITERION

4.6.2.1 Overall Approach

In order to have confidence in the output of CERES subsystem 4.6, it is necessary to establish validation criteria to determine a procedure's reliability for the proposed task. Validation of the CERES subsystem 4.6 procedures depends upon the availability of simultaneous TOA and surface measured net fluxes in both the shortwave and longwave portions of the spectrum, as well as the availability of information concerning atmospheric temperature and water vapor abundance. These validation measurements are to be provided by a combination of long-term programs and specialized field campaigns which are either underway or have been proposed. Recall that CERES subsystems 4.6 and 5.0 process the input data quite differently; however, both subsystems output shortwave and longwave surface fluxes. Thus, it is instructive to compare the results of these two subsystems when they are applied to the same input data.

4.6.2.2 Sampling Requirements & Trade-offs

The surface fluxes derived by the CERES subsystem 4.6 procedures are subject to systematic and random errors arising from two fundamental sources: the algorithm itself and the data input into the algorithm. Errors associated with the algorithm may arise from an imperfect understanding of the involved radiative transfer processes or from the inherent deficiencies of any parameterization which utilizes simplified treatments to describe complex processes. Errors associated with the input data include calibration, radiance to flux conversion, water vapor abundance estimates, etc. The diversity of error sources necessitates the determination of not only the magnitude of the error but also its origin. Identifying the error sources allows for continual improvement in the accuracy of the algorithm. With this in mind, information should be gathered not only for those parameters required in the current algorithms but also for those that have potential impact on the retrieval and are not included in the current versions of the algorithms. Since many of the relevant parameters will remain unavailable until the CERES instrument becomes operational, the pre-launch validation will emphasize the documentation of the uncertainties under very diverse conditions. Post-launch validation will then be concerned with identifying the sources of uncertainties and improving the algorithms. In addition, it is necessary to clearly specify whether the surface fluxes are derived from instantaneous or time-averaged measurements, and whether the quoted errors are systematic which yields information on accuracy (bias), or random which yields information on precision (variance). Note for present purposes, measurements with time scales of order one hour or less are considered to be instantaneous, while measurements with time scales of order one day or longer are considered to be time-averaged.

4.6.2.3 Measures of Success

Table 1 lists suggested accuracy goals for the ATBD subsection 4.6 output parameters. As noted by Suttles and Ohring (1986), a root mean square error of 20 W/m² for instantaneous retrievals and 10 W/m² for gridded monthly averages is considered desirable for both shortwave and longwave surface fluxes. With the acquisition of information during the post-launch phase, and with continual improvements to the algorithms, it is quite possible that a factor of two improvement in the accuracies may be attainable.

More definitive accuracy goals than those presented in Table 1 are dependent upon the errors incurred in obtaining and processing the TOA measurements, the errors associated with the required ancillary datasets, and the inherent errors created during the use of the radiative transfer routines. In addition, the accuracy goals are dependent upon the scientific requirements articulated by the investigators that will use the derived surface fluxes. To clarify the issue, assume that an investigator requires the errors in the derived surface fluxes to be contained within a certain value in order to obtain meaningful results. If the range of acceptable errors does not encompass the errors incurred during data collection and processing then the results will be compromised. Thus, either the investigator's requirements must be relaxed or the data collection and processing techniques must be improved. It is therefore absolutely critical to specify

the accuracy requirements placed upon the simulated surface fluxes as well as the calculated tolerances. It should be noted, however, that as new uses are devised for the retrieved surface fluxes, the accuracy requirements for the data may necessarily need to be modified.

Table 1. ATBD Subsection 4.6 Accuracy Goals

Parameter	Instantaneous (W/m2)	Monthly Average (W/m2)
All-Sky Shortwave	20	10
Clear-Sky Longwave	20	10
Cloudy-Sky Longwave	20	10

4.6.3 PRE-LAUNCH ALGORITHM TEST/DEVELOPMENT ACTIVITIES
4.6.3.1 Existing Validation Studies

The authors of the ATBD 4.6 algorithms have already reported results detailing activities in support of the applicability of the ATBD 4.6 algorithms. It is difficult, however, to fully interpret the results since the comparisons were performed against widely different data sets, and little information was provided concerning the error analyses. Thus, there exists a critical need for a comprehensive program which compares the model outputs using specified TOA measurements to corresponding ground based measured net surface fluxes. Fulfilling this critical need will alleviate much of the ambiguity which exists concerning the accuracy of the algorithms. Before detailing such a program, it is useful to review the results reported in support of the CERES subsystem 4.6 models.

The Li *et al.* (1993b) shortwave algorithm has been tested by comparing the net surface flux deduced from broadband radiance measurements from Earth Radiation Budget Satellite (ERBS) against surface data from two sets of tower measurements. The comparisons indicate that errors in the monthly mean surface insolation can be anticipated to have biases near zero with root mean square errors between 8 and 28 W/m2. The root mean square errors are associated principally with poor representation of surface observations within a grid-cell, and thus, with a sufficient number of observations, it is estimated the root mean square errors could be within 5 W/m2 (Li *et al.*, 1995b). Thus, as noted by Li *et al.* (1993b) it is reasonable to expect the uncertainty in the global climatology of the surface solar radiation budget to be well within 10 W/m2. For an individual estimate corresponding to a particular region and month, however, the uncertainty is less well defined because relatively large amounts of noise (as a result of mis-match) are superimposed upon relatively weak signals. So far all of the validations which have been undertaken suffer from this mis-match problem. Concurrent and collocated observations from space, at the surface, and in the atmosphere are keys to the success of future validations. At the same time, it is possible to detect the influence of certain parameters on the retrieval of the surface radiation budget, if these parameters vary over large scales. For instance, Li (1995) analyzed regional variation of estimation error with respect to the spatial variation of aerosol, using data from the existing global radiation network. Li found that biomass burning and desert dust have considerable impact on the retrieval of the surface radiation budget under clear-sky conditions. The presence of clouds lessens the estimation error considerably. This is rather

encouraging, as aerosol information is generally available under clear-sky conditions. Because of the limited availability of observational data and the skewed distribution of the radiation measurement stations, the Li *et al.* (1993b) algorithm was also evaluated indirectly using an independent satellite-based data set (Li, 1995). While none of the estimation data is sufficiently reliable to be regarded as "ground-truth," a given set may be superior to others in certain respects. Such an indirect validation may help identify several potential sources of uncertainty which await further confirmation from future validations. A variety of validations have indicated that the Li *et al.* (1995a) algorithm works better in the mid-latitudes than in tropical and polar regions. It must be noted, however, that because of the limited number of observations, the magnitude of the error estimates for the tropics and polar regions is far worse than that established for the mid-latitudes.

The current version of the Inamdar and Ramanathan (1994) clear-sky longwave algorithm was formulated to take advantage of TOA radiance information for both the window (8.0 - 12.0 m) and non-window spectral regions. In addition to input from CERES broadband and window channel measured TOA radiances, the Inamdar and Ramanathan procedure is dependent upon surface and near surface (950 hPa) atmospheric temperature data, and total column water vapor measurements. The primary source for the total column water vapor data is the Special Sensor Microwave Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) satellites. The total column water vapor can also be obtained from the detailed water vapor profiles derived from measurements by the Special Sensor Microwave Water Vapor Profiler (SSM/T-2) aboard the DMSP satellites, or by the TIROS Operational Vertical Sounder (TOVS). When compared to detailed radiative transfer models, the Inamdar and Ramanathan clear-sky longwave algorithm yields root mean square errors of approximately 4.4 W/m2 for the tropics and 3.2 W/m2 for the extra-tropics. Moreover, Inamdar and Ramanathan reveal that a comparison of their algorithm results to detailed radiative transfer calculations yields a very high correlation (0.9998) along with a regression line close to 45 which indicates the absence of any bias in the parameterized estimates.

In addition to comparing their algorithms to a detailed radiative transfer model, Inamdar and Ramanathan (1994) have undertaken validation exercises which consider data from the Central Equatorial Pacific Experiment (CEPEX) conducted in March/April 1993, and measurements from the Intensive Observation Period (November 1992-February 1993) at Kavieng Island taken as part of the (TOGA/ISS) program. CEPEX utilized Fourier Transform Infrared Spectroradiometer (FTIR) measurements which were made of the incoming longwave radiances in the 5 - 20 m region. In addition, broadband longwave fluxes were measured with an Eppley Pyrgeometer. Despite certain shortcomings (see Inamdar and Ramanathan, 1994), the results from the standard model agree fairly well with the FTIR and Pyrgeometer measurements. Inamdar and Ramanathan have noted, however, that there are systematic differences between FTIR and the collocated Pyrgeometer measurements which suggest calibration-related uncertainties in the FTIR of 5-8 W/m2. With respect to the broadband flux measurements taken at Kavieng Island, the algorithm compares favorably with mean differences of 3 W/m2 and root mean square differences of approximately 10 W/m2.

Inamdar and Ramanathan (1994) have further noted that thick haze in the atmospheric boundary layer (horizontal visibility < 15 km) has the potential to increase the downward flux by 3 to 5 W/m2. Measurements taken at the ARM sites in Oklahoma and Kavieng tend to confirm this observation, and thus, Inamdar and Ramanathan intend to modify their algorithms with an additional parameter in the form of aerosol visible optical depth.

Gupta *et al.* (1993) conducted sensitivity studies for the cloudy-sky longwave algorithm which demonstrated that most of the errors in the surface longwave fluxes arose from the errors in the input meteorological data. Gupta et al. (1993) found, however, that accuracy goals comparable to those presented in Table 1 are achievable over most tropical and mid-latitude areas. In contrast, Gupta *et al.* (1993) noted that errors over desert and snow/ice-covered areas in the polar regions are considerably higher, reaching

30-40 W/m2 for instantaneous retrievals and 20 W/m2 for gridded monthly values. Nevertheless, Gupta *et al.* (1993) concluded that with the steady improvements expected in the accuracy of the input meteorological data, it should be possible to meet or exceed the accuracy goals suggested in Table 1 over all regions of the globe.

4.6.3.2 Operational Surface Networks

While the previously reported error analyses are informative, a thorough investigation of the applicability of the CERES subsystem 4.6 routines is dependent upon the availability of simultaneously measured TOA satellite radiances and surface net fluxes for both the shortwave and longwave portions of the spectrum. In addition to accurate measurements of TOA radiances and surface fluxes, coincident measurements of temperature and humidity profiles, and cloud properties are necessary for validation. Although limited in extent, a validation dataset has already been produced from measurements taken at the Atmospheric Radiation Measurement/Cloud and Radiation Testbed (ARM/CART) Southern Great Plains (SGP) site in Lamont, Oklahoma during the ARM Intensive Observing Period (IOP) in April 1994, and is available through the CERES/ARM/GEWEX experiment (CAGEX) at NASA/LaRC. The CAGEX database provides measurements taken at the SGP site concerning surface shortwave and longwave fluxes. Interpolation of the nearby soundings from the National Weather Service network provides coincident temperature and humidity profiles over the site, while the CERES Cloud Working Group provides information on the cloud properties retrieved from GOES data. Another pre-launch campaign, ARESE, was undertaken during the fall of 1995 at the SGP site. ARESE was principally designed to provide information addressing important issues concerning the magnitude of shortwave absorption in clouds. Nevertheless, ARESE also provided the opportunity to gather additional surface-measured shortwave and longwave fluxes along with coincident meteorological data which can be incorporated into the CAGEX database and thus can be used for pre-launch validation.

4.6.3.3 Existing Satellite Data

It should be noted that any validation activity which uses satellite radiance data collected after ERBE and before CERES has an inherent source of uncertainty arising from the lack of TOA broadband measurements. While narrowband measurements can serve as surrogates, calibration and bi-directional reflectance effects lead to unquantified errors.

4.6.4 POST LAUNCH ACTIVITIES

4.6.4.1 Planned Field Activities & Studies

For post-launch validation, it is anticipated that collection of high quality surface measurements will continue at the SGP site and will be initiated at the Tropical Western Pacific (TWP) and the North Slope Alaska (NSA) sites. The three ARM sites are expected to be dependable sources of high quality radiometric data along with coincident atmospheric soundings and cloud data. It is critical that the collection of this ground-based data be coordinated temporally and spatially with the collection of the space-borne CERES instrument measurements.

4.6.4.2 Other Post-launch Activities

As currently formulated, the validation of CERES subsystem 4.6 does not require additional EOS-targeted coordinated field campaigns, other satellite data, instrument development, or geometric registration sites.

4.6.4.3 New EOS-targeted Coordinated Field Campaigns

None beyond the needs of SARB (CERES subsystem 5.0).

4.6.4.4Needs for Other Satellite Data

None beyond the needs of SARB (CERES subsystem 5.0).

4.6.4.5Measurement Needs

It is also important that comprehensive observations be made for as many of the potentially relevant parameters as possible. Further data useful for post-launch validation should be available through the NOAA Integrated Surface Irradiance Study (ISIS), which utilizes surface fluxes measured by the NOAA Surface Radiation (SURFRAD) network in the U.S. and by the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN) at selected sites around the globe. Unlike the ARM sites, however, coincident meteorological data may not be available from the SURFRAD and the BSRN sites. Thus, data from other sources will be required to fill the information gap. In addition, information concerning surface shortwave and longwave optical properties will be provided by helicopter surveys. Such helicopter surveys will complement both TOA and ground-based measurements and thereby help in the detection of thin cirrus, aerosol layers, etc. It is further anticipated that high quality radiometric measurements useful for pre-launch and post-launch validation will be provided by an operational instrument tower located in New Kent County, Virginia and operated by NASA/LaRC.

4.6.4.6Needs for Instrument Development

None.

4.6.4.7Geometric Registration Site

None.

4.6.4.8Intercomparisons

For both the shortwave and longwave portions of the spectrum the CERES subsystem 4.6 algorithms provide direct relationships between the measured TOA radiances and the surface fluxes. This contrasts with the CERES subsystem 5.0 algorithms which utilize complex physical models to obtain the surface fluxes from the TOA measured radiances as well as other data. Because both subsystems produce surface fluxes using CERES instrument TOA radiances, the results will be intercompared to check for consistency and to improve the accuracy of both sets of algorithms.

4.6.5IMPLEMENTATION OF VALIDATION RESULTS

4.6.5.1Approach

The process of validating the CERES ATBD 4.6 parameterized radiative transfer algorithms will proceed as follows. TOA and net surface fluxes, which have been measured simultaneously, are collected for both the shortwave and longwave portions of the spectrum. In addition, measurements of the atmospheric temperature and total column water vapor are also acquired. Appropriate high-quality subsets of the available data are then selected for validation. The proposed radiative transfer algorithms are then applied to the measured TOA data to derive simulated surface radiation fluxes which are in turn compared with the measured surface radiation fluxes. A thorough error analysis is then applied to the results of these comparisons. This analysis is intended to provide sufficient information so that a determination can be made regarding the suitability of the radiative transfer algorithms.

It is critical that CERES ATBD 4.6 investigators process an adequate number of pre-launch comparisons so that the radiative transfer algorithms can be applied with confidence during the post-launch op-

eration activities. This necessitates their involvement with current field campaigns, such as ARESE, as well as other long-term efforts. Even during the post-launch sequence of activities, it is prudent to continue validation so as to ensure the quality of the resultant surface fluxes.

4.6.5.2Role of EOSDIS

None.

4.6.5.3Plans for Archival of Validation Data

Validation test results will be archived at NASA/LaRC.

4.6.6SUMMARY

Output Data Parameters: Net shortwave surface flux; Clear-sky downward longwave (> 5.0 m), window (8.0 - 12.0 m) and non-window surface fluxes (W/m²); and Cloudy-sky downward and net longwave surface fluxes.

Validation Criteria: Root mean square errors of 20 W/m² for instantaneous retrievals and 10 W/m² for gridded monthly averages for both shortwave and longwave surface fluxes.

Validation Data Sources: A limited validation dataset has been produced from measurements taken at the ARM/CART Southern Great Plains (SGP) site, and is available through the CERES/ARM/GEWEX experiment (CAGEX) at NASA/LaRC. The CAGEX database provides measurements taken at the SGP site concerning surface shortwave and longwave fluxes. It is anticipated that collection of high quality surface measurements will continue at the SGP site and will be initiated at the Tropical Western Pacific (TWP) and the North Slope Alaska (NSA) sites. Further data useful for validation should be available through the NOAA Integrated Surface Irradiance Study (ISIS), which utilizes surface fluxes measured by the NOAA Surface Radiation (SURFRAD) network in the U.S. and by the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN) at selected sites around the globe.

Validation Procedure: The validation of the CERES ATBD 4.6 parameterized radiative transfer algorithms will proceed by gathering the necessary input data (simultaneously measured TOA and net surface fluxes for both the shortwave and longwave portions of the spectrum, atmospheric temperature, and total column water vapor), applying the radiative transfer algorithms to the measured TOA data to derive simulated surface radiation fluxes, comparing simulated fluxes with measured surface radiation fluxes, and conducting a thorough error analysis of the results of these comparisons.

Validation Archive: Validation data and results will be made available through anonymous ftp and/or through the World Wide Web.

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